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RADIATION DIAGNOSTICS IN EXTREMELY HARSH ENVIRONMENTS*

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ABSTRACT

Some recent Trailmaster experiments have required the use of rather delicate radiation diagnostics in hostile environments. We have developed instrumentation for use near high-explosive magnetic flux compression generators and near the noisy environment of high energy capacitor banks. These include some rather unique "fly-away" designs for x-ray imaging and spectroscopy, and other optical techniques for plasma temperature and field measurements. We will show some representative data and will also discuss an on-going program for the determination of magnetic field via atomic spectral line splitting and/or broadening.

INTRODUCTION

In recent years, experimentation in explosive environments and in conditions where instrumentation may encounter serious damage, has made it necessary to develop some rather uuique diagnostics. We will discuss techniques used in studies done with explosively driven magnetic flux compression generators (Trailmaster) at Los Alamos National Laboratory in Ancho Canyon and other experiments done in the vicinity of electrically noisy capacitor banks. We wish to show that sophisticated and delicate instrumentation can be used to collect valuable information and still maintain their integrity and be usable after these conditions. It is necessary to use film in some of these experiments, and a need to recover film and the instrumentation has made it necessary to develop some new procedures.

The Trailmaster series of imploding plasma experiments[1,2] is aimed at collapsing a thin aluminum foil with a multi-megampere, submicrosecond circuit by a flux compression generator and a fast plasma compression opening switch. The goal is to obtain an intense source of soft x-rays from the thermalization of plasma kinetic energy when pinch on axis occurs. The characterization of such an experiment requires diagnosing the driver performance, power flow, and the imploding foil plasma.

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Our part in the experiments was restricted mainly to the radiation diagnostics. The successful production of x-rays from the Trailmaster Z-pinch plasma increased our effort to study the x-rays. Four different x-ray pinhole cameras were fielded, three time-resolved and one time-integrated. A curved crystal x-ray spectrometer was also incorporated into one of the pinhole housings.

Visible (350-680 nm) spectroscopy can, under certain conditions, reveal the nature of the plasma from the charge state of the imploding aluminum ions or the continuum radiation. A spectrometer that initially used film was later adapted to a time-resolved optical multichannel analyzer (OMA). We have studied continuum emissions from aluminum and copper fuses[3] and have compared these with blackbody emissions and determined the temperature. Later in this discussion, we will show representative signals and blackbody curves fitted to the experimental data.

The knowledge of magnetic and electric fields associated with experiments is extremely important. Faraday rotation[4] has already been used successfully for a multitude of experiments. At higher magnetic fields we hope to use techniques associated with the Zeeman effect. Atomic parameters can serve as very sensitive indicators of conditions in the plasma. Both spectral splitting and broadening effects due to magnetic and electric fields (Stark effect) can be useful indicators of these fields. On-going studies together with Jaycor[5] will provide information to fully develop these diagnostics and will be briefly mentioned here.

The bulk of our experimental experience in the hostile environment is based on developing diagnostics for the Trailmaster program. The emphasis of the first series of shots was considered as a learning process, and we tried to maximize the success of experimental techniques and diagnostics. The next series of shots will concentrate on obtaining an optimal pinch and copious quantities of soft x-rays. We feel we have learned how to field experiments in the high explosive environment and are confident that we can diagnose the next series of Trailmaster experiments with state-of-the-art diagnostics.

X-RAY IMAGING

Each of the three time-integrated pinhole cameras used in the Trailmaster program had distinct designs, and had to withstand the shock of high explosives and make film recovery possible. They were designed to look at different spectral regions of x-rays at pinch time. Two of the cameras were aimed axially, one at either end of the pinch, and the third looked radially. They utilized various methods of protecting the film from the physical damage of the blast and eliminating film exposure after the event. As shown in Figs. 1 and 2, the cameras were ruggedized by "hefty" metal parts. All cameras were required to be vacuum tight and be able maintain vacuum in the 10^{-6} torr range. The bolts were drilled or slotted to minimize virtual leaks and the vacuum pumpout holes were designed to minimize the entry of stray light that might cause film fogging. The two axial cameras used inertial shutters which incorporated a one mm glass rod that broke from the explosive shock and closed the spring-loaded shutters. The pinhole cameras used 100 micron pinholes and the geometry was set to give a magnification of one for the bottom camera, 0.81 for the top camera and 0.5 for the radial one. The cameras required filters for the proper band pass of x-rays and to minimize film fog from visible light during the period, before the shot, when shutters are open.

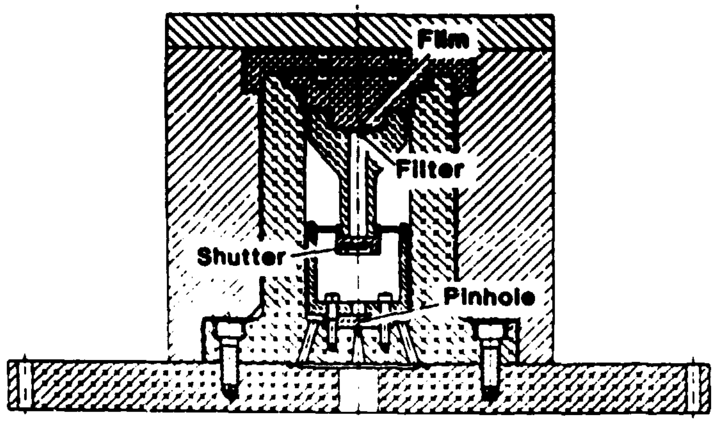

Fig. 1. The top axial x-ray pinhole camera. The camera is mounted on a 5-cm-thick aluminum plate. Film is loaded during assembly of the vacuum chamber and shutter is opened just before a shot.

The characteristics of the three cameras are:

1. The top axial camera (Fig. 1) was mounted on a 5 cm thick aluminum plate and was enclosed and held down with a lead and wood "porta potti". This was done to minimize damage upon hitting the canyon walls and to minimize the distance the camera flies during the experiment. The x-ray energy range was determined by filters and in this experiment 100 nm of aluminum on a 100 nm thickness of paralyne-N were used. The filters provided an x-ray window in a region from 30 to 75 ev and another window from a couple hundred ev to beyond a kilovolt. The filters were placed at the film plane and were essentially in contact with the film.

2. The radial camera (Fig. 2) was enclosed in a 2.5-cm-thick steel cylinder, and steel and aluminum parts held the pinholes and the x-ray crystal. In addition, the outside of the camera was wrapped with lead to minimize the destructive impact with the canyon walls. An explosive detonator actuated shutter was used as shown in Fig. 2. The detonator, which was triggered from a timing circuit, broke the half inch glass rod and the springs drove small apertures past the pinholes. The film was exposed during the period when the apertures and the pinholes were colinear and provided shutter times of approximately 100 microseconds. The camera used two pinholes so that a stereoscopic image could be obtained or if needed, two different x-ray filters could be used. The filters were 1000 nm thickness Kimfoil mounted at the pinhole and provided a window 70 ev and higher. A scheme of layering different types of film in a "stack" (see Fig. 2) provided some additional x-ray energy discrimination. In this case, the top layer would be sensitive to soft x-rays and the the bottom layer to the harder (above 1 kv) x-rays that would penetrate the top film.

The x-ray spectrometer associated with the radial camera (Fig. 2) used a convex crystal. This geometry is very useful in conditions where space is limited and a large spectral dispersion is necessary. The dispersion in this system is determined by the Bragg condition, the curvature of the crystal and the distance from the film. Filters are used to restrict the x-rays to a predetermined spectral band. Figure 3 shows a typical spectrum obtained with a lithium fluoride crystal under test conditions. In the Trailmaster experiments we used a lead-stearate crystal that would cover a range from 170 to 350 ev. X-ray spectroscopy is particularly useful in identifying the elemental composition and the charge state of the plasma.

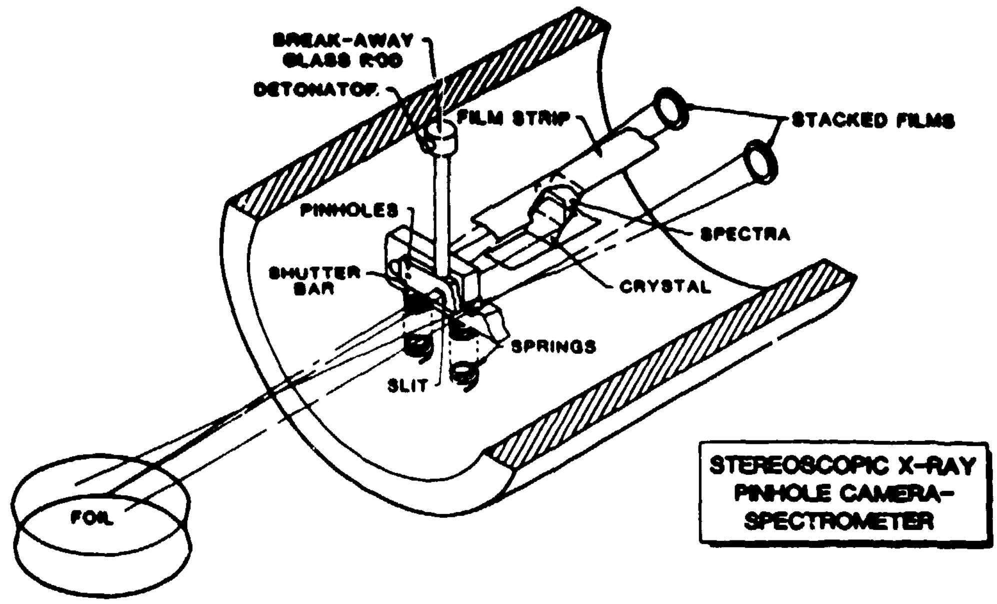

Fig. 2. The radial x-ray pinhole camera and spectrometer combination. The pinholes, film location, shutter mechanism, and x-ray spectrometer are shown. The x-ray filters are located in front of the pinholes and spectrometer slit.

It becomes necessary for accurate high temperature measurements when the black body distribution peaks in the x-ray region. To improve these measurements a time resolved, strip-line-gated, high-resolution spectrometer system is being developed.

3. The bottom pinhole camera had a 0.5 mil beryllium filter at the film plane. The range of x-rays was from 600 ev and upwards to a region where the film would no longer respond. This camera was situated in the position where high explosives would do minimal damage and was also designed to be driven into a pile of sand for later recovery. Unfortunately, its nearness to the plasma melted the beryllium filter and destroyed the film. Figure 4. shows the molten aluminum coated camera after it was recovered from the experiment.

Images that were obtained in the latest Trailmaster shot are shown in Fig. 5. The axial image is viewed through a series of apertures at the top of the plasma region. The radial camera provided two pictures, one from the top layer of film (soft x-rays) and the other from the bottom layer (1.49 Kev Al K α lines).

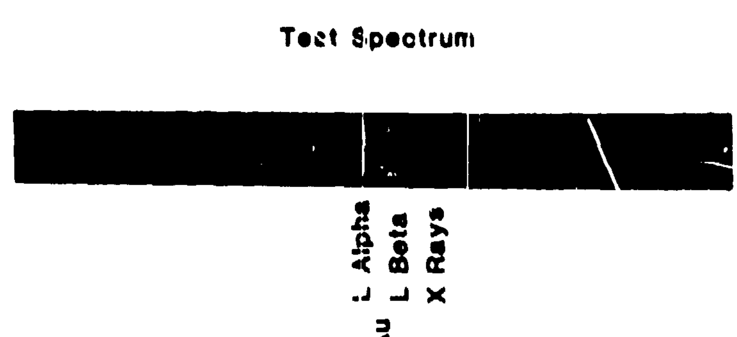

Fig. 3. Spectrum from x-ray spectrometer with lithium fluoride crystal showing Au L transitions under test conditions. The actual experiment used lead stearate for a crystal and covered x-ray energies from 150 to 300 ev.

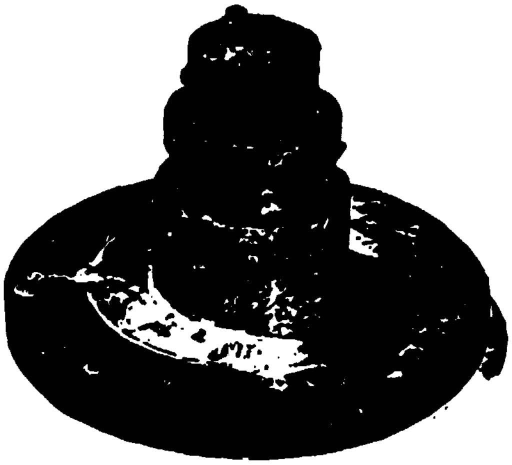

Fig. 4. The bottom, axial pinhole camera. Covered with molten aluminum. This camera is located in a region where damage can be caused by plasma effects.

In this experiment the pinch was broad and not centered and therefore only one of the radial views provided an image. Views from a visible framing camera confirm the observations of the pinhole cameras. The curved crystal spectrometer was set to sample a small region at the center of the expected pinch and therefore showed no detailed structure but only a uniform background.

TIME RESOLVED X-RAY IMAGING

On earlier Trailmaster experiments a 4-channel microchannel-plate-gated imaging system, "4-eyes" was developed for a radial view of the implosion. This design was successful for imaging in the visible with 12 ns gate times. Schematic of this is shown in Fig. 6. The gated x-ray camera was obtained by placing an x-ray screen/window combination at the port window at which the "4-eyes" telescope was pointed. All four channels were timed to look at various stages of the pinch by triggering them from an XRD signal. The x-ray signals were rather low on these shots and no useful signal was obtained. However, the potential and the future usability of this technique were proven and will be pursued.

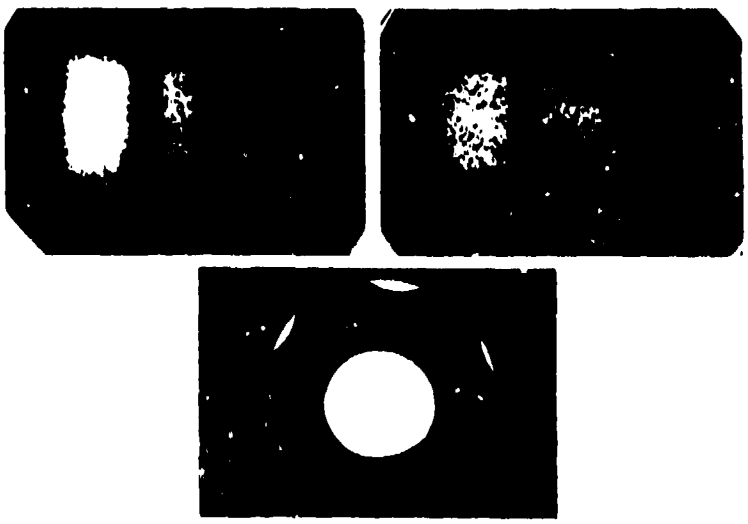

Fig. 5. Pinhole images in the latest Trailmaster experiments. The axial and radial cameras show a uniform plasma radiation. The top pictures show the radial views. The left picture shows the hard x-rays (1.49 Kv aluminum); the right picture shows soft x-rays (70-300 ev). The bottom picture is an axial view of the plasma.

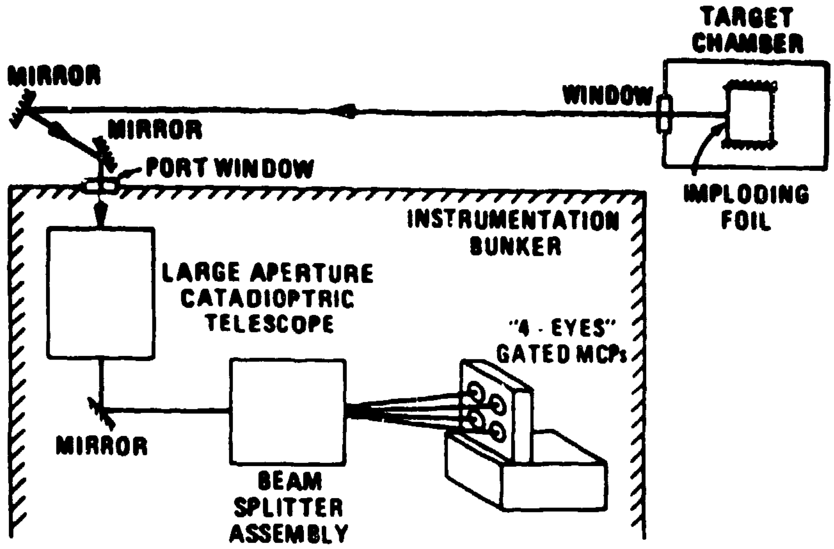

Fig. 6. Time resolved x-ray imaging. A fluorescein on the port window produced visible light from the x-rays and these were imaged by the microchannel-plate-gated camera.

VISIBLE SPECTROSCOPY

Visible spectroscopy can be used to determine the temperature of a plasma and also provide information about the plasma dynamics from spectral line broadening or splitting. Spectroscopic techniques were used successfully on the Trailmaster implosions and on studies of switches and fuses. Temperature is an especially useful parameter in plasma studies and proved invaluable in the fuse tests. We have carried out time-integrated spectroscopic studies using film and time resolved studies using an OMA.

The early spectroscopic studies of the Trailmaster implosion plasmas were done with film at the exit port of a spectrometer. An optical path of approximately 10 m was flooded with helium to minimize the absorption in the 240-340 nm spectral range. The spectrometer was protected from the explosive shock inside a steel cabinet surrounded by sandbags. The light was collected at the entrance slit via telescope mirrors which were destroyed in the experiment. A sample of such data is shown in Fig. 7. After corrections were made due to film and spectrometer response, a fit to blackbody curves was made and a temperature was determined as shown in Fig. 8. The time integrated temperature measurement over the pulse length provided an average temperature of 1.6 ev for the plasma.

The time evolution of the temperature and the spectral line distributions provide valuable insight into theoretical modeling, and therefore, it becomes important that we time-resolve our spectroscopic data.

A spectroscopic study of aluminum and copper fuse plasmas demonstrated usefulness of the time resolved OMA techniques. In these experiments the optical signals were received over an optical fiber. One end of the fiber was positioned in the fuse plasma the other end at the entrance slit of the spectrometer. The spectrometer and its electronic detectors were placed in a screen box to minimize ground loops and electronic noise. The trigger to the OMA was also received over an optical fiber from the light produced at a closing switch at crowbar time of the capacitor bank. A typical example of fuse data with a fitted blackbody curve is shown in Fig. 9. Similar data (Fig. 10) observed from a colder region of the plasma show additional spectral lines.

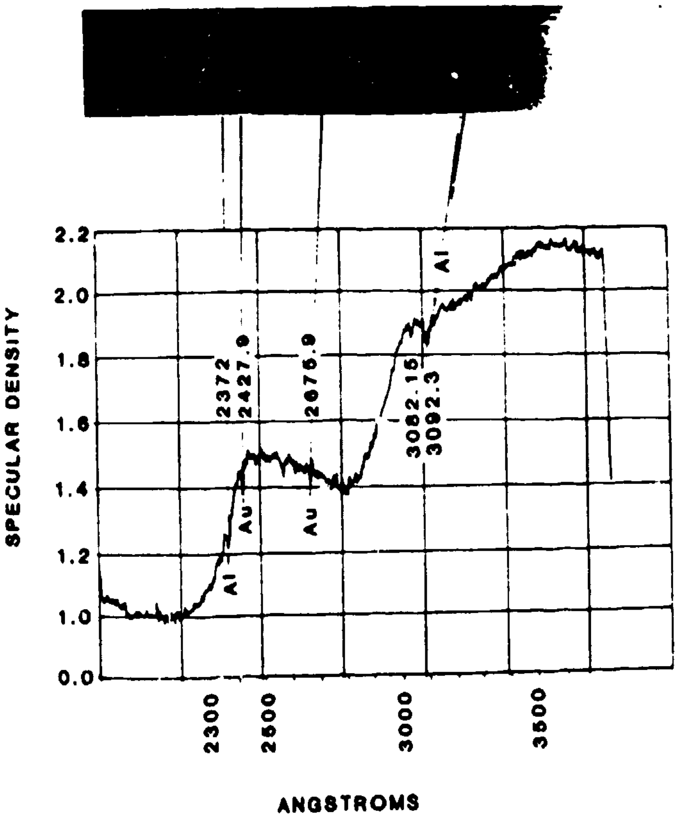

Fig. 7. Data from a visible time-integrated spectrometer. Picture of the spectra and the associated densitometer trace are shown.

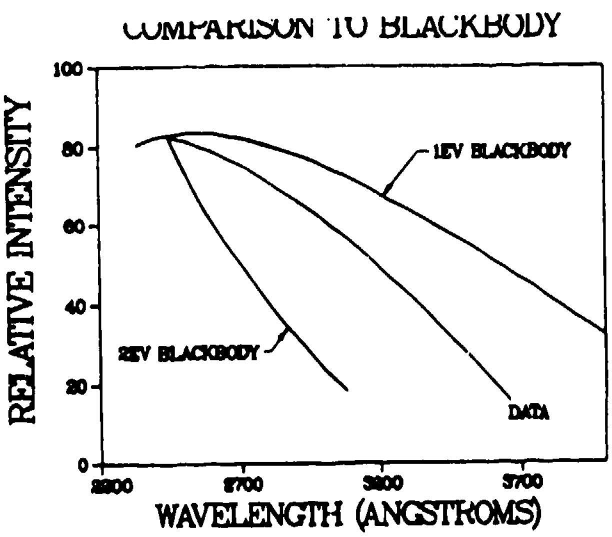

Fig. 8. The plasma temperature of the Trailmaster shot as determined from the time integrated spectrometer data that was shown in Fig. 7.

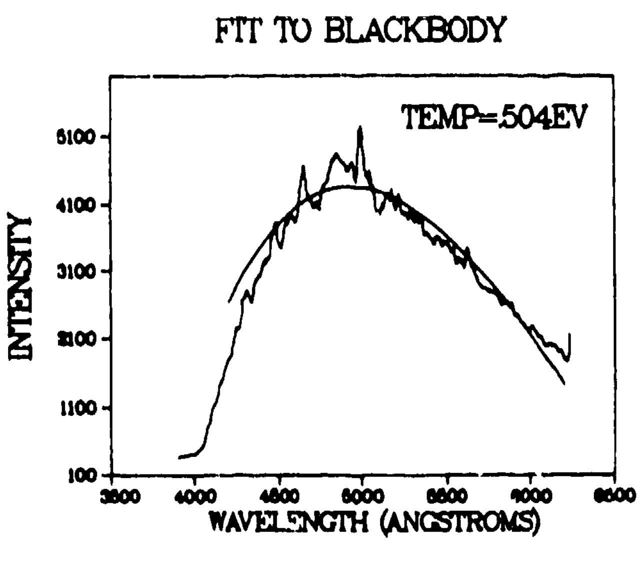

Fig. 9. Blackbody fit to data from an aluminum fuse. The data were collected with an OMA which has a time window of 3 μsec in this experiment.

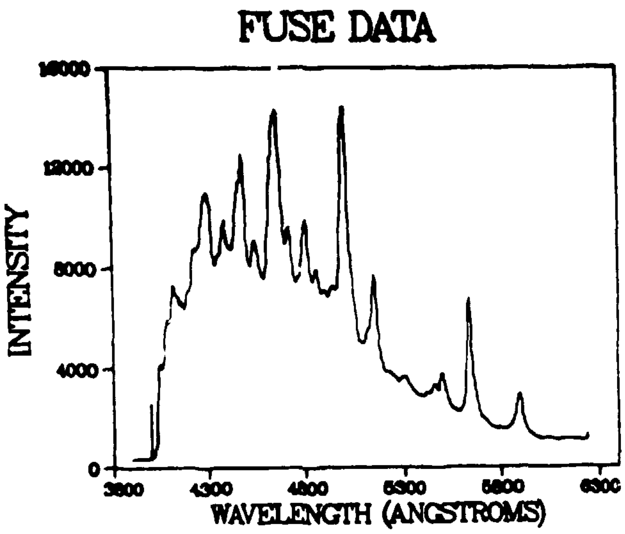

Fig. 10. OMA data observed from a colder region of the fuse plasma. The spectral lines are from various stages of ionization of the aluminum atoms.

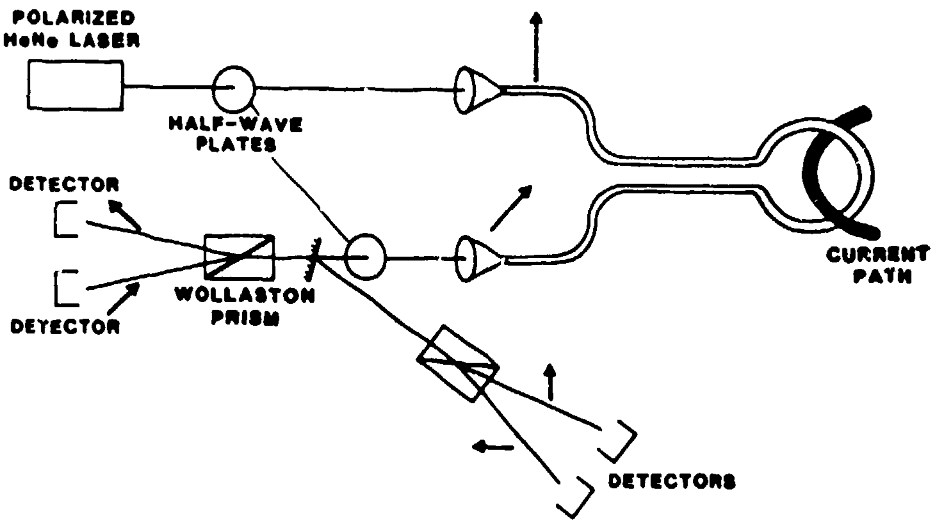

Fig. 11. Faraday rotation for current and field measurements that is used in pulse power experiments. Observation of the angle of rotation in the single mode fiber is observed and is proportional to the field.

The data shown used a 3 μs time window. In this case, the cold plasma was observed from the region of the aluminum electrodes and show some multiply ionized aluminum transitions. It is possible to use visible-UV spectroscopy to determine temperatures from the peak of the blackbody curve from 0.4 to 1.2 ev and beyond by fitting the data to the tail of a blackbody.

FIELD MEASUREMENTS

It has always been awkward to make current and the associated electromagnetic field measurements with electrically conducting diagnostics in pulse power experiments. The electrical noise and ground loops have caused serious problems. Fiber optic sensors have helped solve some of these problems. Faraday rotation has provided magnetic field measurements in the range from below a hundred kilogauss to a megagauss. These techniques are presently used to determine the currents in the Trailmaster, explosive generator, and switch experiments. The principle of operation of a Faraday current sensor is based on the Faraday effect in a single mode fiber. The effect is a magnetically induced rotation of the plane of polarization of linearly polarized light. This rotation is measured by placing the fiber between polarizers and monitoring the transmitted light with a photodiode. The fiber is looped (see Fig. 11) in the region of the experiment where the measurement is made and it is usually the only part destroyed during the experiment.

However, for very high fields, the shock wave can destroy the fiber before the measurement is finished, consequently there is a need to develop other techniques for higher fields. The Zeeman effect has been used to measure magnetic fields in laser-produced plasma experiments. We, together with Jaycor, are developing these techniques, on Proto II at Sandia National Laboratory, for field measurements in the ten megagauss region. The helium-like carbon triplet (227.09-227.79 nm which are $1s2s\,^3S_1 - 1s2p\,^3P_{2,1,0}$ transitions) present at the high temperature produced in the implosion experiments is a reasonable candidate for these studies. The spectral splitting of these lines is about 0.2-0.3 nm per megagauss.

The two spectrometers used in these experiments used a 2400 g/mm grating with a resolution of 0.015 nm. One of the spectrometers was coupled to a streak camera and the other one to the OMA. Optical signals were transmitted to the instruments with fused silica optical fiber bundles. The transmission of these fibers at 227.0 mm was about 70% per meter. The OMA used 20 meters of fiber and the streak camera 5 meters. The preliminary data look promising and the experiments are continuing.

CONCLUSION

The Trailmaster program and other associated projects have led us to develop techniques that are necessary and unique. We have demonstrated that it is possible to diagnose plasma parameters in almost any type of hostile environment, and have been able to recover and reuse all diagnostics. Work is in progress to sharpen the resolution and improve the performance of each diagnostic, and implement new diagnostics as the parameter range of the experiment increases.

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